Unit 12
Cryogenics for Accelerator Magnets

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Scope of the lecture

- Cryogenics for Accelerator magnets
  1. History
  2. Cryogenic fluids
  3. Design options for superconducting magnets
  4. Thermodynamic cycles for refrigerators
  - Designs issues and material properties for cryogenic applications

References

- Steve Van Sciver,
  - “Helium Cryogenics”, Plenum Press
  - USPAS Course Notes, “Cryogenics for Accelerator Magnets”
- Jack Ekin
  - “Experimental Techniques for Low-Temperature Measurements”, Oxford University Press
- Ray Radebaugh
  - “Application of Cryocoolers to Superconducting Systems”, ASC short course, Seattle, 2006

History of Cryogenics

Cryogenics is the science of producing temperatures below ~200K

- Faraday demonstrates ability to liquify most known gases by first cooling with a bath of ether and dry ice, followed by pressurization
  - he was unable to liquify oxygen, hydrogen, nitrogen, carbon monoxide, methane, and nitric oxide
  - The noble gases, helium, argon, neon, krypton and xenon had not yet been discovered (many of these are critical cryogenic fluids today)
- In 1848 Lord Kelvin determined the existence of absolute zero:
  - 0K=-273C (=-459F)
- In 1877 Louois Caillettet (France) and Raoul Pictet (Switzerlan) succeed in liquifying air
- In 1883 Von Wroblewski (Cracow) succeeds in liquifying Oxygen
- In 1898 James Dewar succeeded in liquifying hydrogen (~20K!); he then went on to freeze hydrogen (14K).
- Helium remained elusive; it was first discovered in the spectrum of the sun
- 1908: Kamerlingh Onnes succeeded in liquifying Helium

Candidate Cryogenic fluids

- Boiling point and heat of vaporization for key gases (at atmospheric pressure):

Gas	Boiling point [K]	Heat of vaporization [J/cm^3]
Xenon	166	
Krypton	120	
Oxygen	90	243
Argon	87	
Nitrogen	77	161
Neon	27	104
Hydrogen	20	31.4
Helium	4.2	2.6

Cryogens for SC magnets

- The two most important cryogens for SC magnet applications are Nitrogen and Helium.
  - Nitrogen is readily available; liquid nitrogen is by far the most readily available means of accessing cryogenic temperatures for applications
  - For LTS superconductor applications, Helium is the cryogen of choice
    - Helium is a liquid down to absolute zero
    - It is inert, and has a superfluid component below 2.17K (Lambda point)
  - Neon is used for some niche applications, but is not readily available
  - Liquid hydrogen is used for niche applications as well
    - It has nice cryogenic properties
    - it is highly flammable => implies that fault scenarios and transport / transfers add unwanted risks.

Crogenic fluids: nitrogen

- Nitrogen:
  - Largest single constituent in the atmosphere
  - Produced industrially by fractional distillation of air
  - In liquid form (77K at atmospheric pressure) it serves to:
    - Freeze and preserve foods
    - Preserve biological specimens
    - Cool material for the creation of high-strength metals
    - Cool electronic sensors
  - Key parameters:
    - **Expansion ratio, liquid-gas: 1:694**
    - Molecular Weight: 28.01
    - Boiling point: 77K
    - Freezing point: 63K
    - Critical temperature: -146.9C
    - Critical pressure: 33.5Atm.

Cryogenic fluids: helium

- Helium:
  - Boiling point: 4.2K
  - Does not freeze
  - Critical temperature: 5.1K
  - Critical pressure: 2.26Atm
  - Expansion ratio, liquid-gas: 1: 754

Note: The worlds supply of Helium is limited, as it escapes from the atmosphere in gas form unless captured

Density

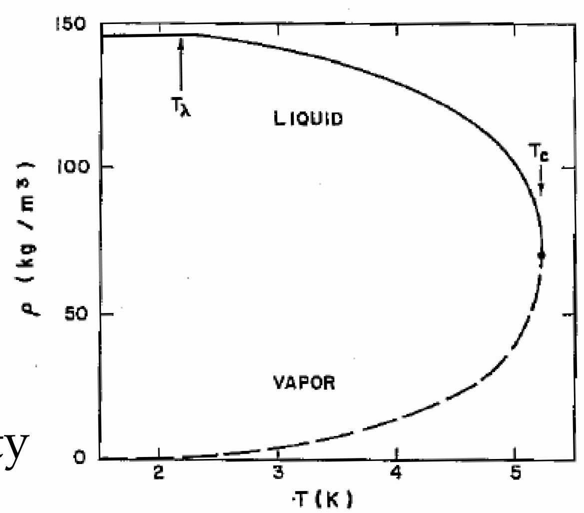
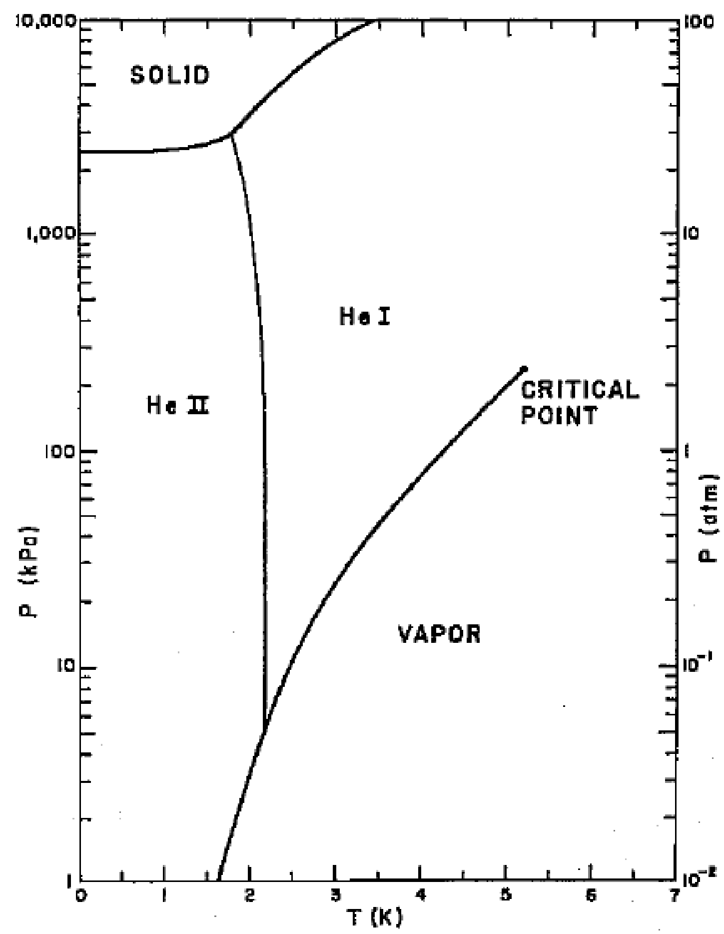


Fig. 3.4. Density of saturated liquid helium.



Helium characteristics

- Novel characteristics of liquid Helium:
  - Helium has a triple point in the phase diagram, distinguishing liquid, gas, and supercritical regimes
  - Helium undergoes a phase transition at 2.17K, named the Lambda point; below T_λ the fluid behaves as if composed of both normal and superfluid components

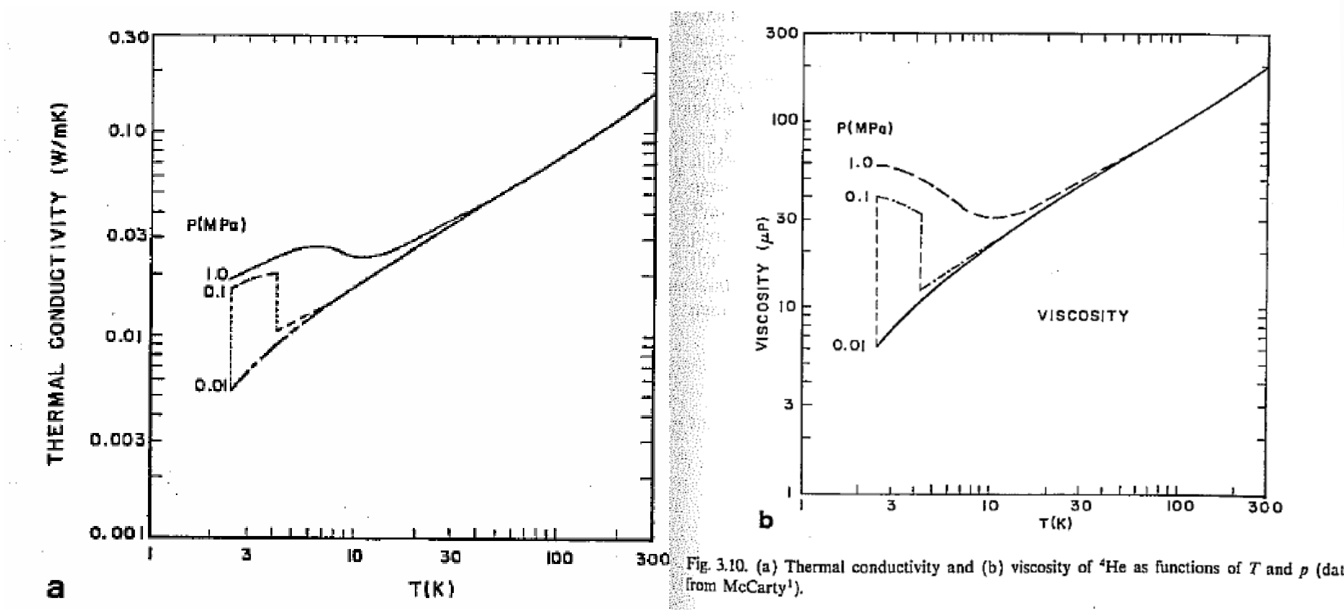
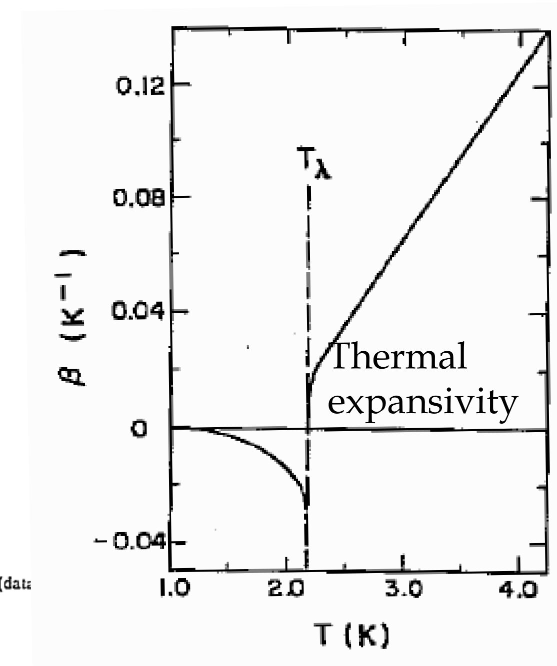
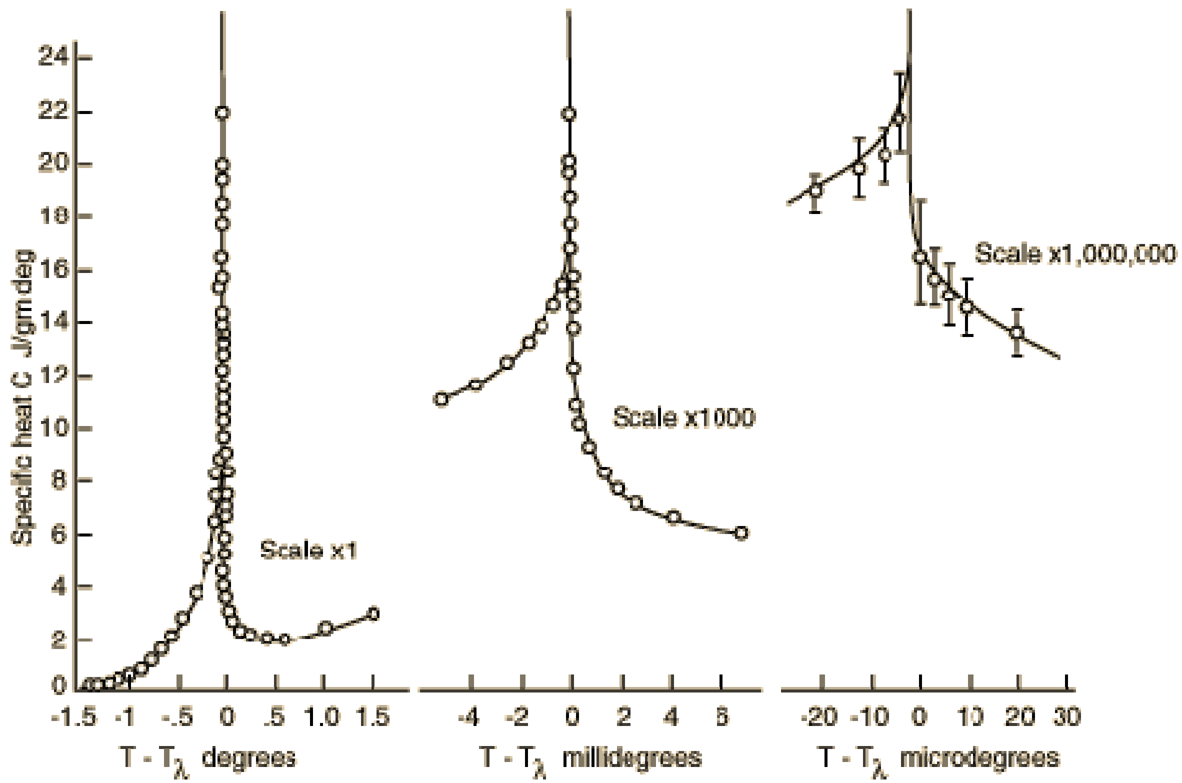


Fig. 3.10. (a) Thermal conductivity and (b) viscosity of [4]He as functions of T and p (data from McCarty[1]).



Helium characteristics

- Helium undergoes a phase transition with extremely novel behavior of the specific heat
    - Part of the fluid condenses in a Bose-Einstein condensate (very similar to the formation of superconductivity) with zero viscosity.



From Buckingham and Fairbank

Cryogenic Design options for superconducting magnets

- Cryogenics for Accelerator magnets
  - History
  - Cryogenic fluids
  - Design options for superconducting magnets
  - Thermodynamic cycles for refrigerators
  - Designs issues and material properties for cryogenic applications

Cryogenic design considerations

- To cool a system, a designer has the following options:
  1. Use the cold-head of a cryocooler refrigerator system to cool the magnet via conduction. No cryogens are used (other than in the refrigerator itself)
     - Used mainly by HTS applications; under rare circumstances with LTS
     - ALS superbend magnets cooled by cryocoolers
  2. Use liquid cryogens, supplied in dedicated low-loss storage containers called dewars. The system benefits from liquid-solid heat transfer and the heat capacity of the replaceable cryogens; typically used in research applications
  3. Use liquid cryogens that are contained in a closed system and recondensed with a refrigeration system. This approach is typically used for large facilities. Examples: CERN, Fermilab.

Varying temperature

- To attain temperatures other than that available from liquid cryogens at nominal pressures:
  1. change pressure!
     - Range of available temperatures is limited
       - Increasing pressure is limited by cryostat design
       - Pumping speed and heat load dictates lowest attainable temperature
       - Transitioning through the λ-point is difficult due to spike in heat capacity
     - Requires appropriate system design (pressure vessel issues, danger of introducing other gasses when sub-atmospheric…)
  2. By separating the cryogenic space from the sample/magnet, it is sometimes possible to increase the temperature by applying a separate heater
     - This is easiest when the system uses a cryocooler – no cryogens to replenish

Basic cryogenic systems

- A typical research cryogenic magnet system

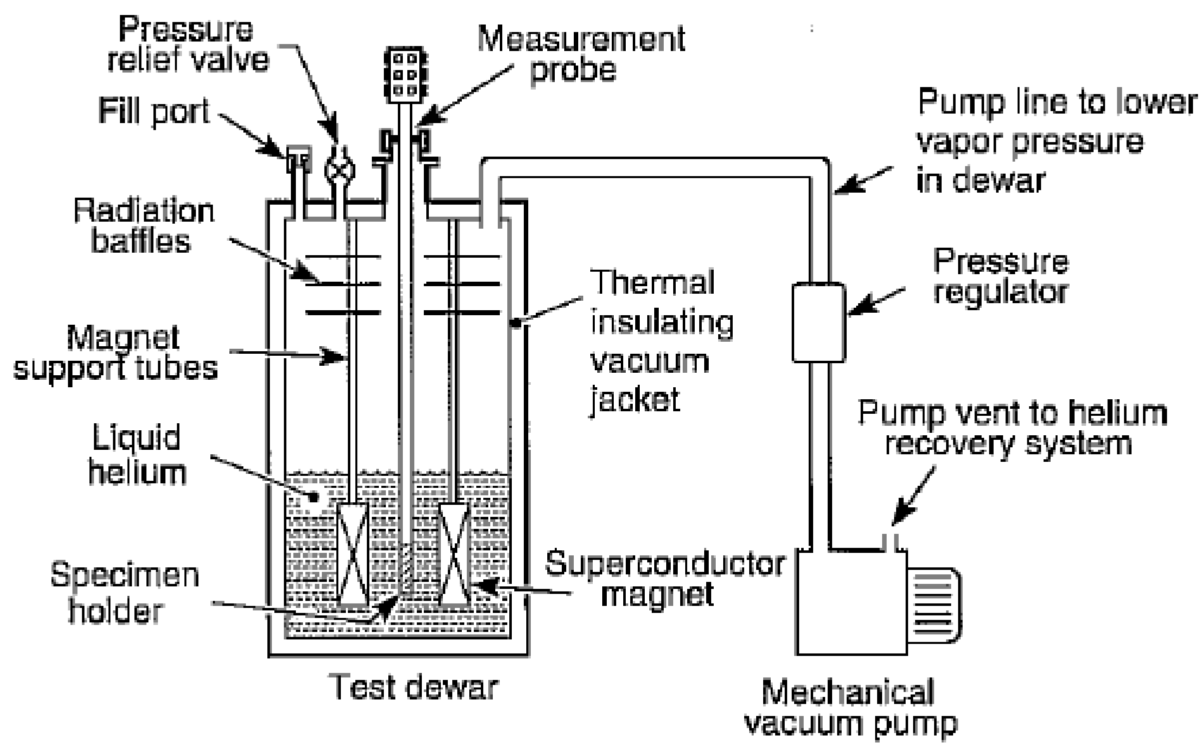


Fig. 1.1 Schematic of an immersion measurement probe in a cryogenic liquid with a vacuum pump for lowering the boiling temperature of the cryogen bath.

A typical lab experience: Transferring Helium

- Helium has a low latent heat of vaporization
  - Transfer line must be well insulated
  - If there are residual liquids (e.g. air or nitrogen), much He can be wasted freezing them

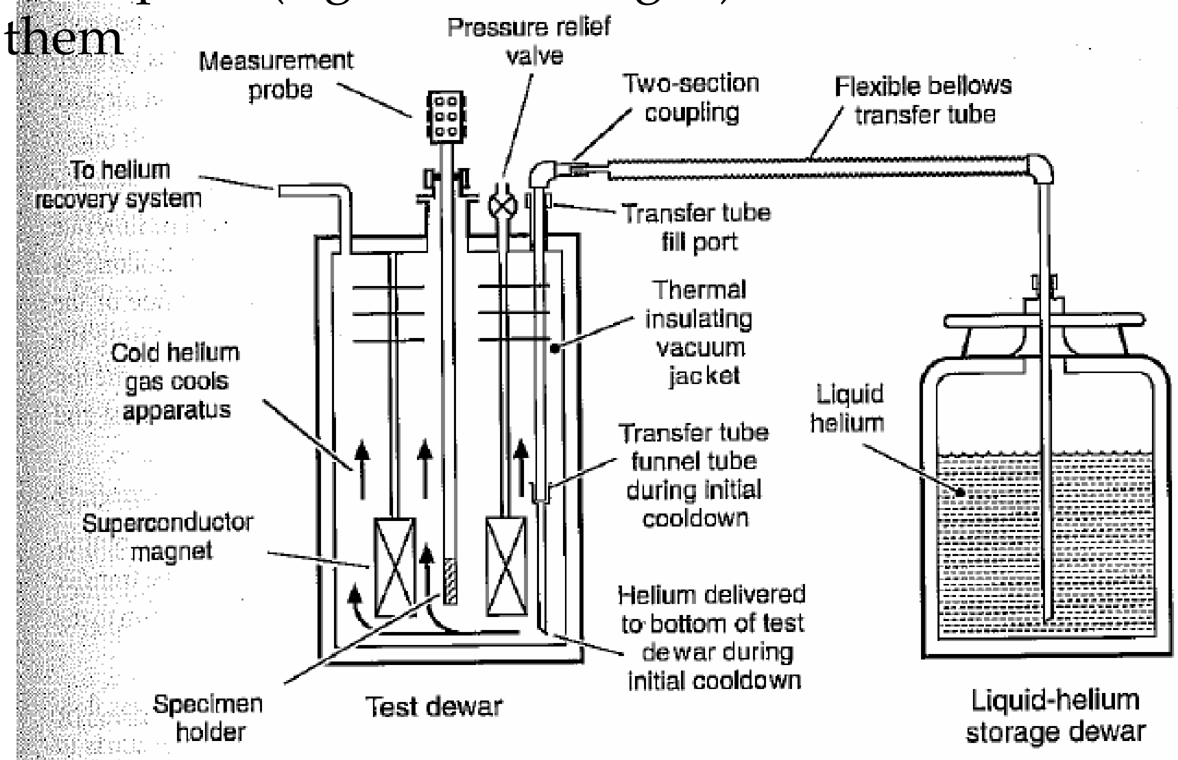


Fig. 1.18 Transferring liquid helium from a storage dewar into a test dewar. The transfer tube must be double walled (not shown), with the space between the walls evacuated to thermally insulate the inner fluid line from the outside world.

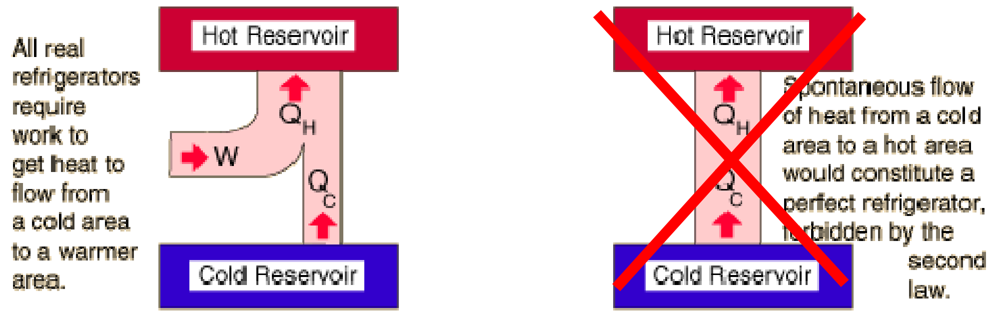
Cryogenic Design options for superconducting magnets

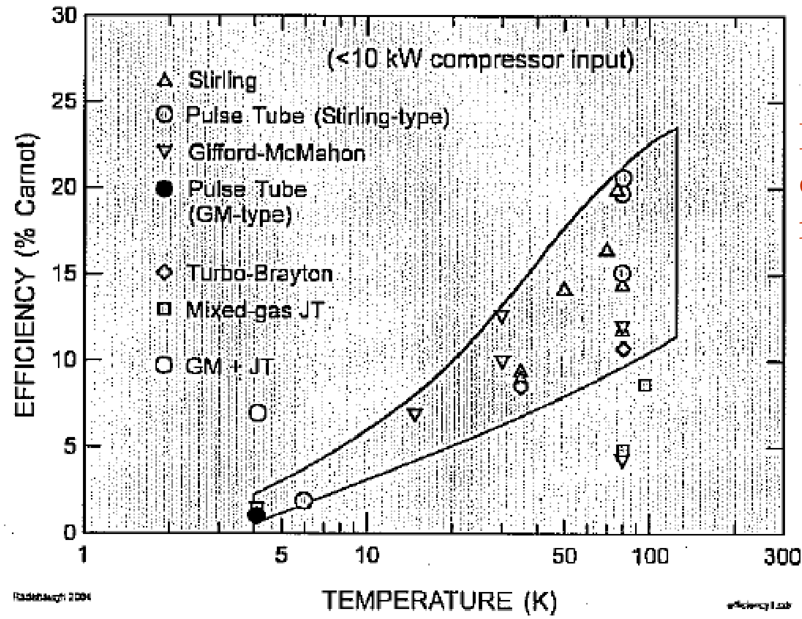
- Cryogenics for Accelerator magnets
  - History
  - Cryogenic fluids
  - Design options for superconducting magnets
  - Thermodynamic cycles for refrigerators
  - Designs issues and material properties for cryogenic applications

- Some basic thermodynamic concepts:
  - The Carnot cycle defines the most efficient “heat engine” cycle

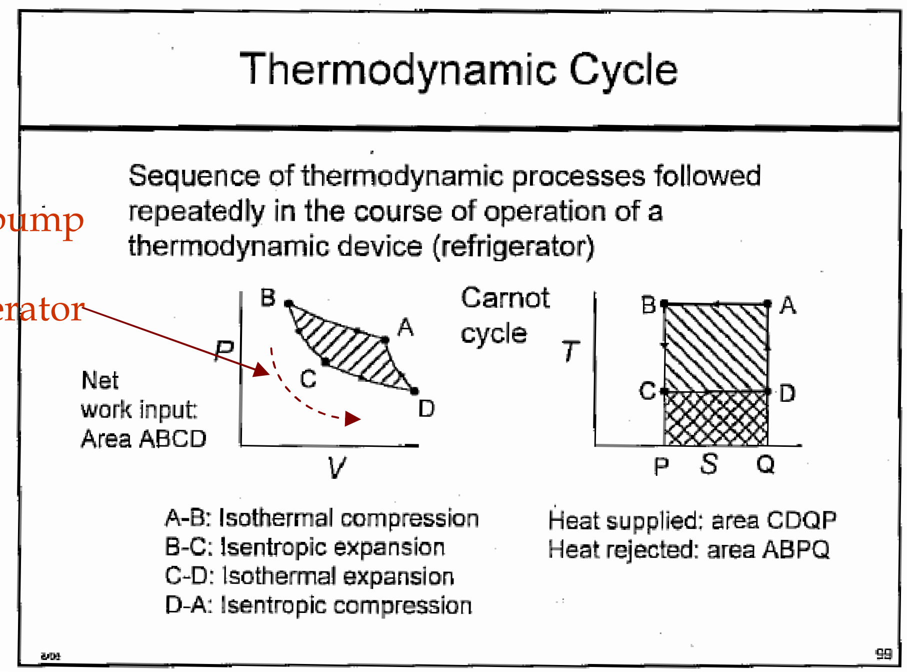
$$C_{eff} = \frac{Q_c}{Q_h - Q_c} = \frac{T_c}{T_h - T_c}$$

Second Law of Thermodynamics





Heat pump or refrigerator

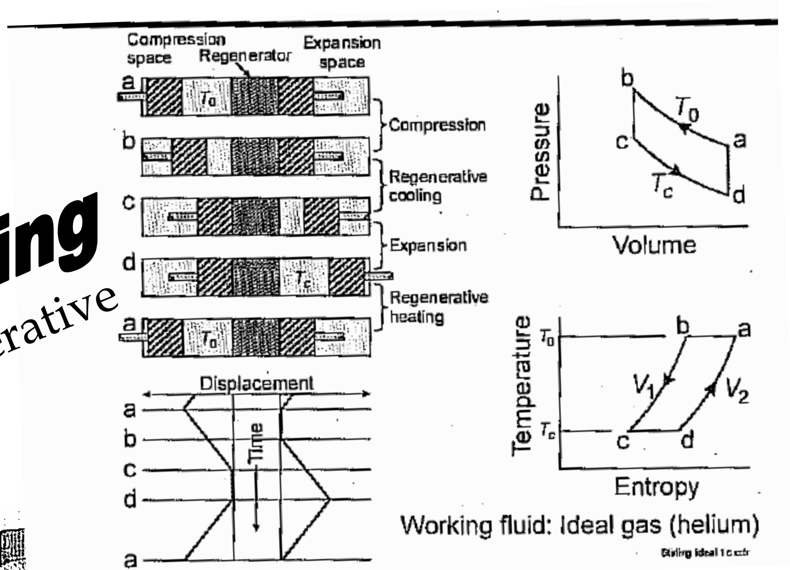


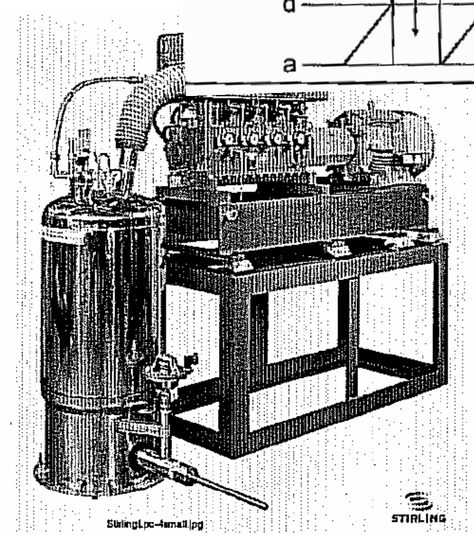
Real refrigerators

- Real refrigerator cycles commonly used for liquifying cryogens:

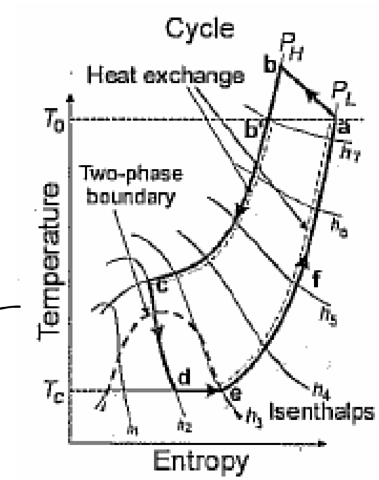
Stirling

Regenerative cycle

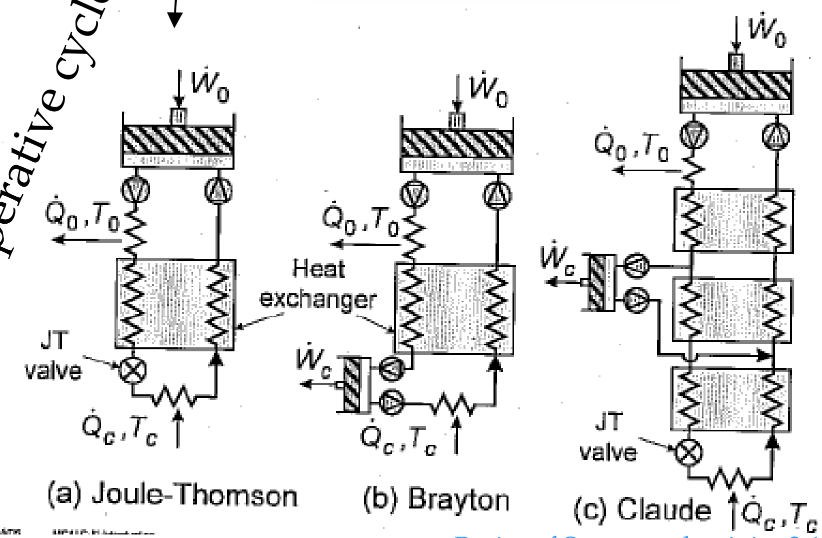




- 4 cylinders
- 44 L/hr LN_2
- 4200 W @ 80 K
- 3100 W @ 65 K
- 44 kW input
- 26% Carnot @ 80 K



Recuperative cycles



Large scale HeII systems

- It is possible to get below the λ-point via pumping, but it is not a practical large scale approach
- The most common means is through the use of a Joule-Thompson expansion valve (J-T valve)
- The G-10 plate ("Lambda plate") is designed to minimize thermal contact between HeI and HeII regions

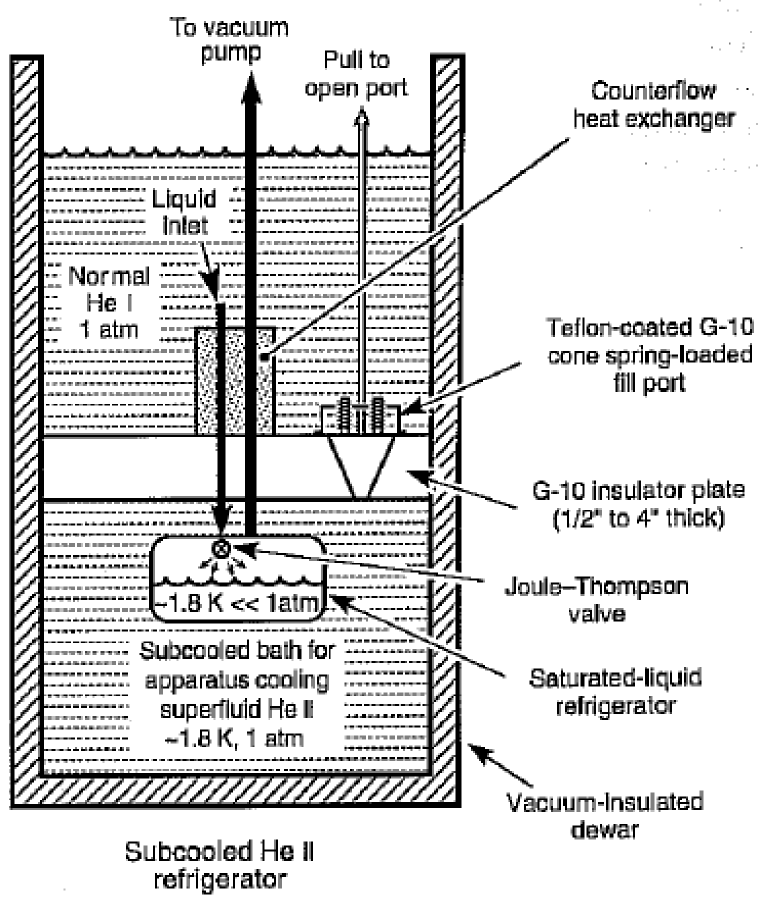
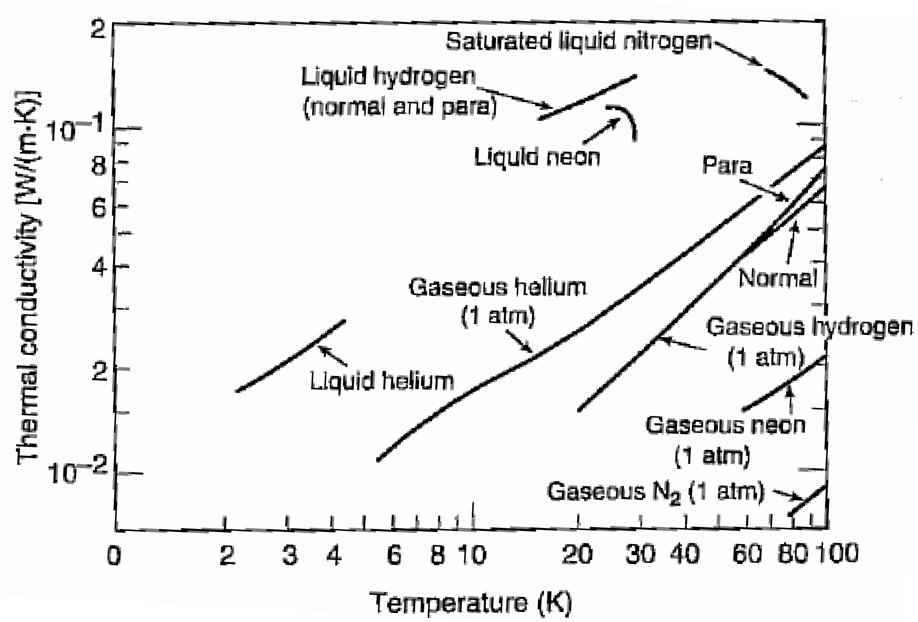


Fig. 1.16 Schematic diagram of the components of a saturated-liquid-container refrigerator for obtaining continuous high-cooling power at superfluid-helium temperatures (adapted from Pfotenhauer et al. 1997).

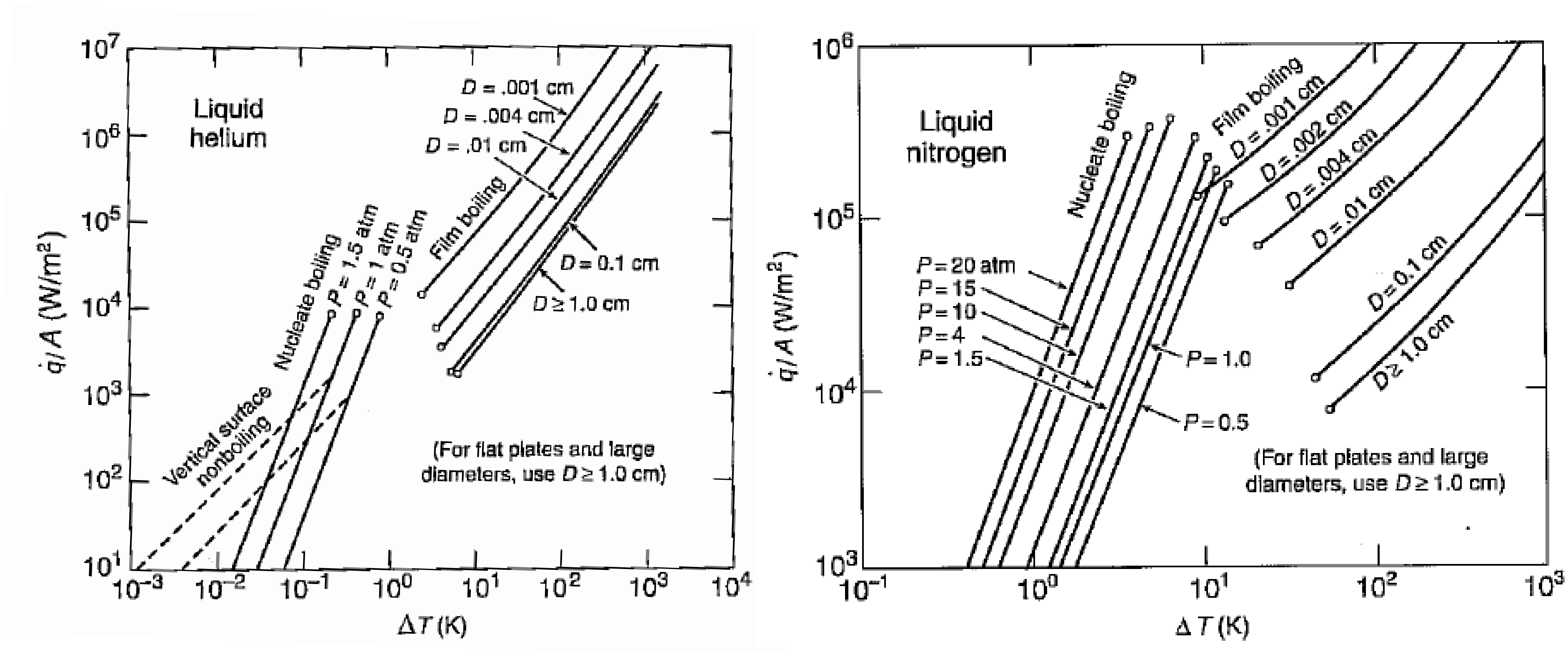
Designing Cryogenic systems: thermal conductivity of cryogens

- A key issue with cryogenic systems is understanding / designing for thermal performance
  - We need to know:
    - Where is heat coming from?
    - What is the temperature at critical locations (e.g. magnet, leads)?
    - What are the thermal gradients?
- To start, we need to know gradients within the cryogens:



Heat transfer to cryogens

The heat transfer vs wall ΔT from surfaces to cryogens depends strongly on the the flow state (forced flow or convection)



Cryogenic design with superfluid helium

- Superfluid helium has extraordinary thermal conductivity; for many calculations it is effectively infinite.
  - Heat is transported by heat "sound" waves – "*second sound*"
  - The whole bath heat capacity is available for cooling a localized spot!
  - The largest temperature drop is then at the fluid-metal interface
- For small temperature drops, solid-fluid interfaces at temperatures below T_λ exhibit Kapitza conductance
- For larger temperature drops, a thin layer of He I forms => drop in thermal conductance

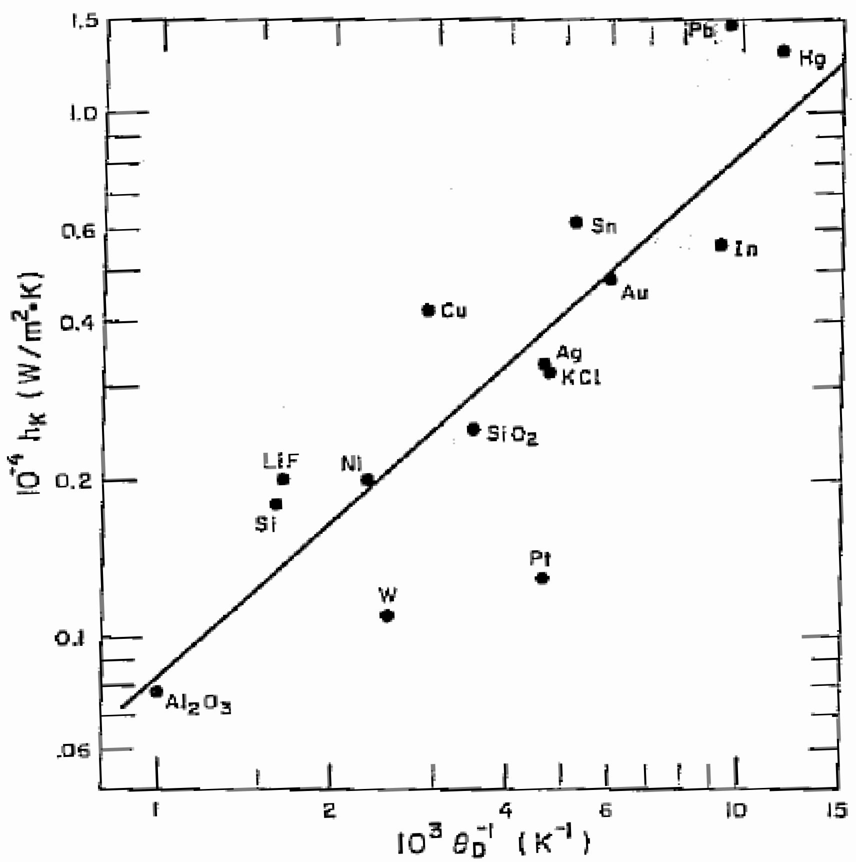
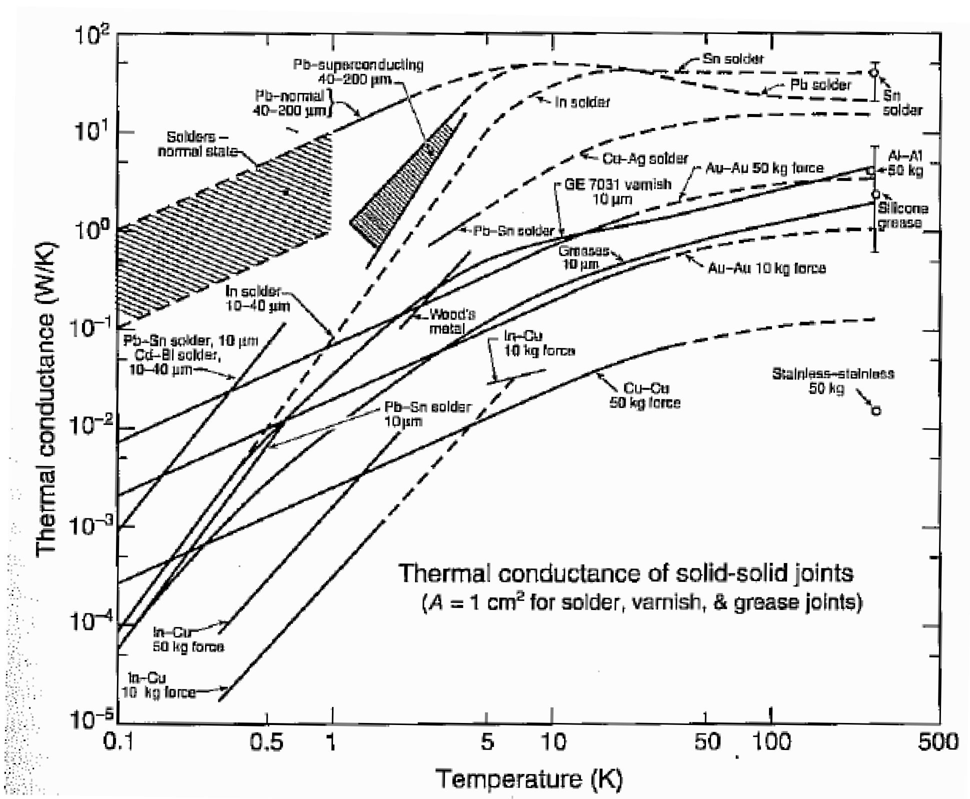
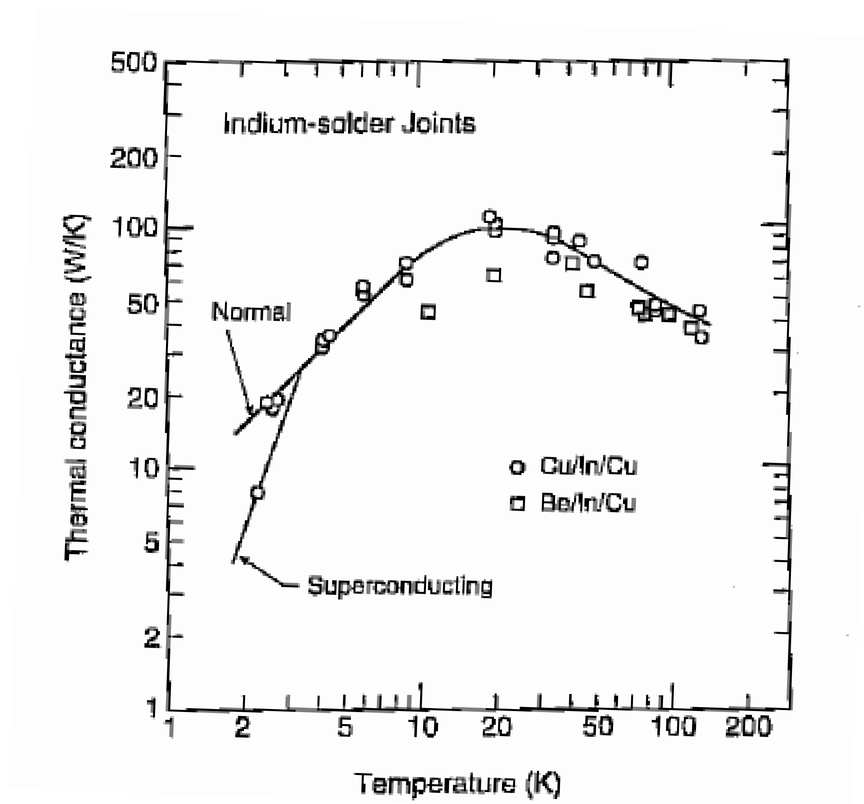


Fig. 5.20. Kapitza conductance at 1.5 K—largest values observed for each solid (compi
Challis[32]).

Cryogenic design considerations: joints between solids

- Joints are critical components in cryogenic systems
  - Significant variation in thermal conductance between different joints
  - Materials, pressures have significant impact
  - Changes in joint conditions over time may have significant impact on cryogenic loads





Material properties for cryogenic applications

- Designers must carefully select materials for cryogenic applications:
  - Material strength changes
  - Material modulus may change
  - Many materials undergo phase changes (e.g. become brittle)
  - Differential thermal expansion between materials may result in unwanted stress/strain states
  - Thermal conductivity varies significantly between various materials
    - Especially true <~20K, where physics of thermal transport can change

- *Basic rules:*
  - *Monitor thermal loads and temperature variations*
  - *Monitor thermal contraction and stress states during cooldown*

Thermal conductivity of technical materials for cryogenic applications

Table 2.3. Thermal Conductivity (in W/m · K) for Some Technical Alloys, Glasses, and Plastics[a]

Material	0.1 K	0.4	1	4	10	40	80	150	300 K
Al 5083	—	—	0.7	3	8	34	56	80	120
Al 6063	—	—	8	35	87	270	230	200	200
Brass (70% Cu, 30% Zn)	0.06	0.2	0.7	3	10	37	65	85	120
Cu + 30 Ni	0.006	0.03	0.1	0.5	2	~12	~20	~25	30
Cu + 2 Be	—	—	—	1.9	5.1	20.5	35	—	—
Constantan	0.006	0.02	0.1	0.8	3	14	18	20	23
Iconel	—	—	0.05	0.4	1.5	7	10	12	14
Manganin	0.006	0.02	0.06	0.5	2	7	13	16	22
Silicon bronze (96% Cu, 3% Si, 1% Mn)	—	—	—	—	1.5	7	14	—	25
Soft solder (60% Sn, 40% Pb)	—	—	—	16	42	52	52	—	~50
Stainless steels (18/8)	0.008	0.03	0.08	0.3	0.7	5	8	11	15
Wood's metal	—	—	—	4.0	12	20	23	—	—
Nylon	—	0.0006	0.003	0.01	0.04	—	—	—	—
Polystyrene	—	—	0.01	0.03	—	—	—	—	—
Pyrex	0.0003	0.003	0.01	—	—	—	0.5	0.8	1.1
Soft glass	—	—	0.015	0.1	0.2	0.3	0.5	—	—
Teflon	0.00002	0.0004	0.004	0.05	0.1	0.2	0.2	—	—
Vitreous silica	—	—	—	0.1	0.1	0.3	0.5	0.8	1.4
Epoxy	0.00004	0.0007	0.007	0.06	0.06	—	—	—	—

[a] After White.[2]

Thermal contraction of technical materials for cryogenic applications

Table 2.5. Linear Thermal Contractions Relative to 293 K[a]

Substance T(K):	0	20	40	60	80	100	150	200	250
Aluminum	41.4	41.4	41.2	40.5	39.0	36.9	29.4	20.1	9.6
Copper	32.6	32.6	32.3	31.6	30.2	28.3	22.1	14.9	7.1
Germanium	9.3	9.3	9.3	9.4	9.3	8.9	7.3	5.0	2.4
Iron	20.4	20.4	20.3	19.9	19.5	18.4	14.9	10.2	4.9
Lead	70.8	70.0	66.7	62.4	57.7	52.8	39.9	26.3	12.4
Nickel	23.1	23.0	22.9	22.6	21.8	20.8	16.5	11.4	5.4
Silicon	2.16	2.16	2.17	2.23	2.32	2.40	2.38	1.90	1.01
Silver	41.0	41.0	40.3	38.7	36.5	33.7	25.9	17.2	8.2
Titanium	15.1	15.1	15.0	14.8	14.2	13.4	10.7	7.3	3.5
Tungsten	8.6	8.6	8.5	8.4	8.1	7.6	5.9	4.0	1.9
Brass (65% Cu, 35% Zn)	38.4	38.3	38.0	36.8	35.0	32.6	25.3	16.9	8.0
Cu + 2 Be	32.4	32.4	31.9	31.6	30.0	28.3	22.0	16.0	7.0
Constantan	—	—	26.4	25.8	24.7	23.2	18.3	12.4	5.85
Invar[b]	4.5	4.6	4.8	4.9	4.8	4.5	3.0	2.0	1.0
304, 316 Stainless steel	—	29.7	29.6	29.0	27.8	26.0	20.3	13.8	6.6
Pyrex	5.6	5.6	5.7	5.6	5.4	5.0	3.95	2.7	0.8
Silica (1000° C)[c]	−0.1	−0.05	0.05	0.2	0.3	0.4	0.5	0.4	0.2
Silica (1400° C)[c]	−0.7	−0.65	−0.5	−0.3	−0.2	−0.05	0.2	0.2	0.1
Araldite	106	105	102	98	94	88	71	50	25
Nylon	139	138	135	131	125	117	95	67	34
Polystyrene	155	152	147	139	131	121	93	63	30
Teflon	214	211	206	200	193	185	160	124	75

[a] Units are $10^4 \times (L_{293} - L_T)/L_{293}$. Sources of data include *Thermophysical Properties of Matter* (1977), Corruccini and Gniewek (1961), and *American Institute of Physics Handbook* (1972). Compiled by White.[2]

[b] The expansion of Invar NiFe alloys containing ~36% Ni is very sensitive to composition and heat treatment.

[c] These silicas were aged at 1000° C and 1400° C.

Yield strength and modulus of technical materials for cryogenic applications

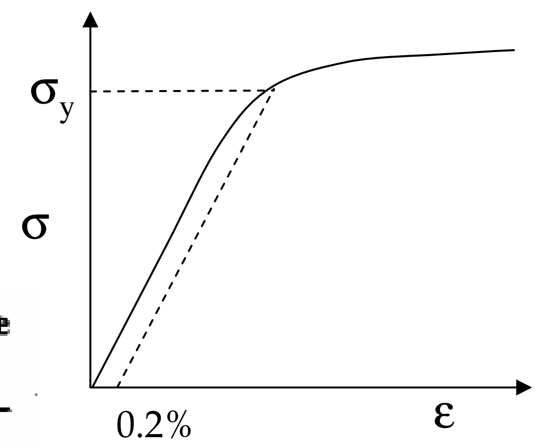
Table 2.6. Yield Stress σ_y of Several Materials as a Function of Temperature (MN/m^2)[a]

Material	σ_y(0 K)	σ_y(80 K)	σ_y(300 K)
304L-SS	547	460	406
6061-T6 Al	345	332	282
OFHC-Cu (Annealed)	90	88	75
Cu + 2 Be	752	690	552
Brass (70% Cu, 30% Zn)	506	473	420
Inconel X-750	940	905	815
G10-CR	758	703	414
Teflon	130	65	20

Table 2.8. Young's Modulus E of Several Materials as a Function of Temperature (GN/m^2)[a]

Material	E(0 K)	E(80 K)	E(300 K)
304L-SS	201	205	190
6061-T6 Al	87	79	68
OFHC-Cu (annealed)	139	139	128
Cu + 2 Be	134	130	121
Brass (70% Cu, 30% Zn)	—	145	110
Inconel (X-750)	—	223	210
G10-CR	36	34	28

[a] See Refs. 4 and 17.



Cryogenics: conclusions

- The "game" in cryogenics is understanding and controlling heat (source, distribution), and accounting for thermal contraction-based stresses.
- We cannot avoid the second law: heat loads at low temperatures are "expensive"
- The choice of cryogenic system design depends strongly on the operating conditions: temperature, duty factor, reliability required, etc.